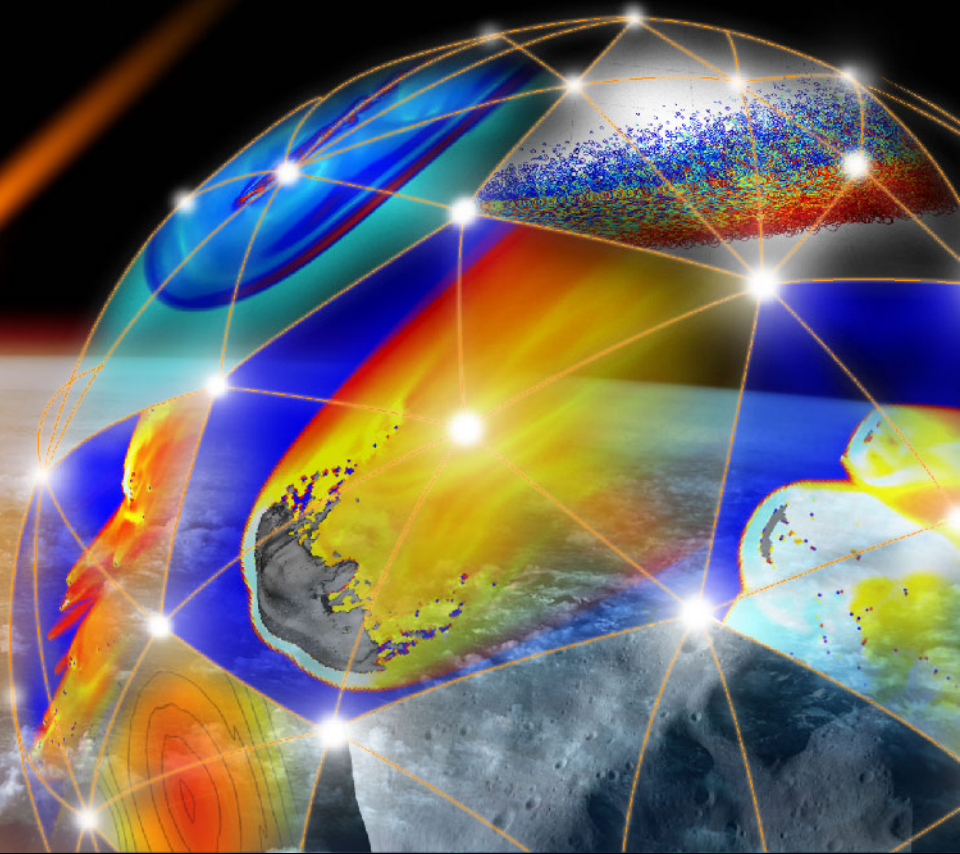




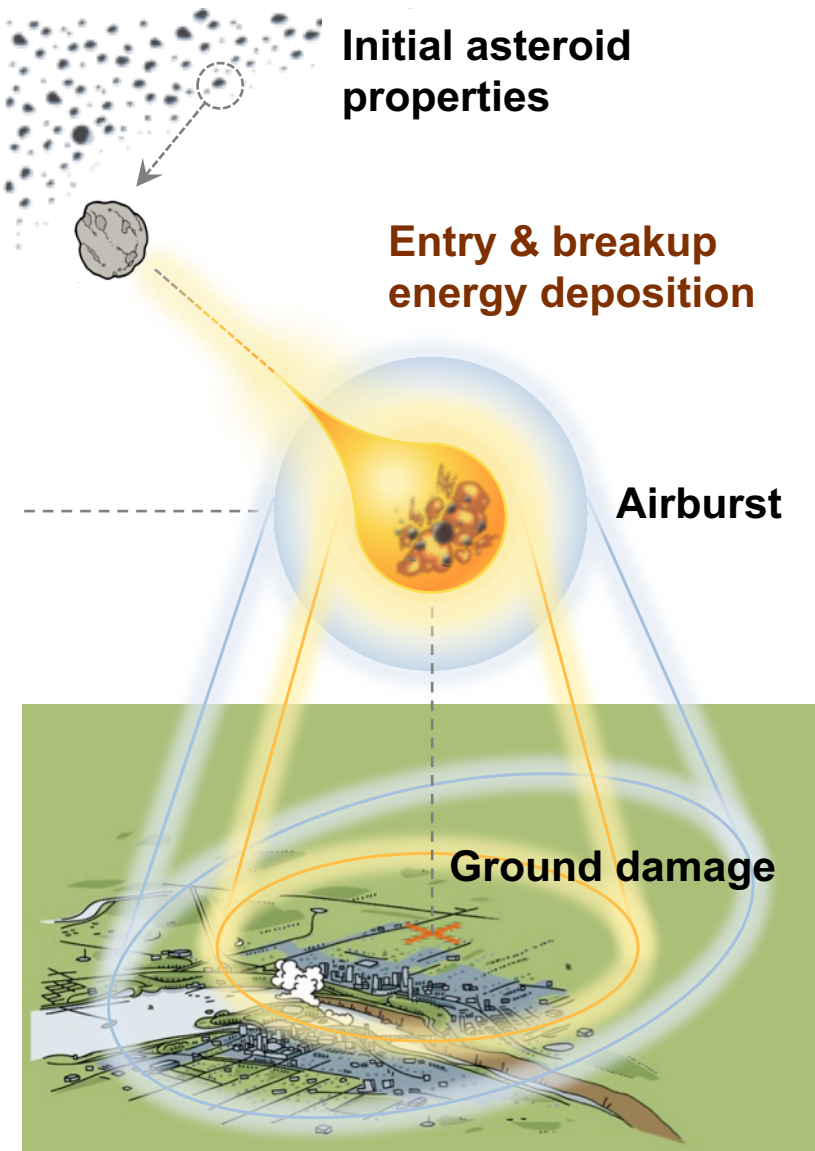
# Modeling the Atmospheric Breakup of Varied Asteroid Structures: Inferences for the Chelyabinsk Meteor

**Lorien Wheeler, Donovan Mathias**  
Asteroid Threat Assessment Project  
Engineering Risk Assessment Team  
NASA Ames Research Center

Planetary Defense Conference  
May 18, 2017 – Tokyo, Japan

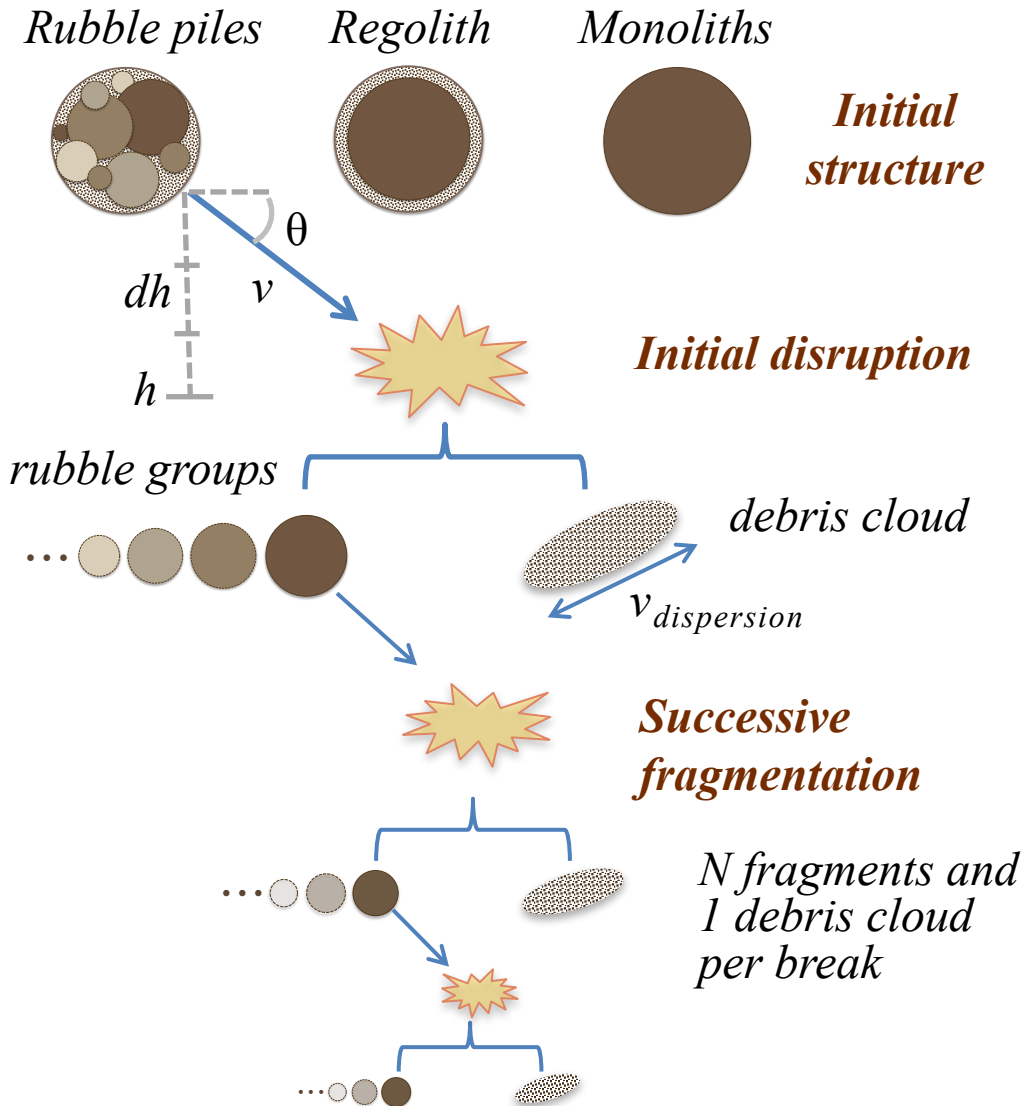


# Asteroid Impact Risk Modeling



- Fragment-Cloud Model (FCM)
  - Models energy deposited in the atmosphere during entry and breakup
  - Energy deposition used to estimate airburst altitudes and ground damage
- FCM results can also be matched to observed meteor light curves
  - Infer pre-entry asteroid properties
  - Investigate different breakup characteristics
  - Guide model refinements
  - Bound parameter ranges
- Current effort is expanding FCM to represent varied initial asteroid structures

# Fragment-Cloud Model (FCM)



## Flight integration:

$$dm/dt = -0.5\rho_{air}v^3A\sigma$$

$$dv/dt = \rho_{air}v^2AC_D/m - g\sin\theta$$

$$d\theta/dt = (v/(R_E+h) - g/v)\cos\theta$$

$$dh/dt = v\sin\theta$$

## Fragmentation condition:

$$\rho_{air}v^2 > \text{Strength } (S)$$

## Fragment strengths increase with decreased size

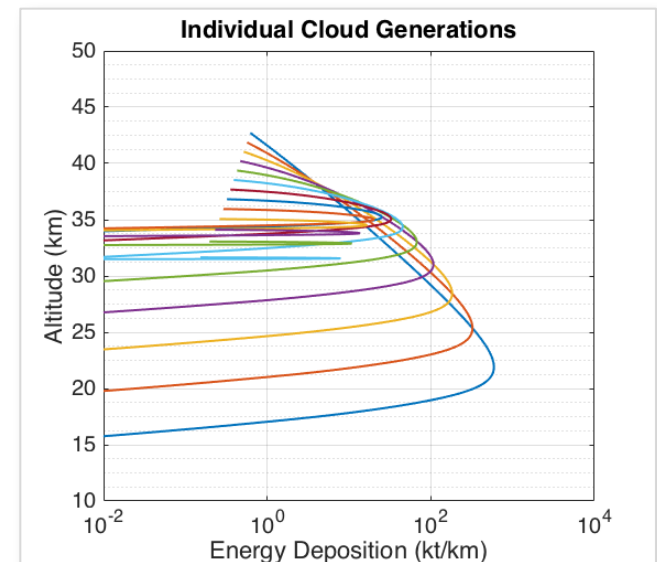
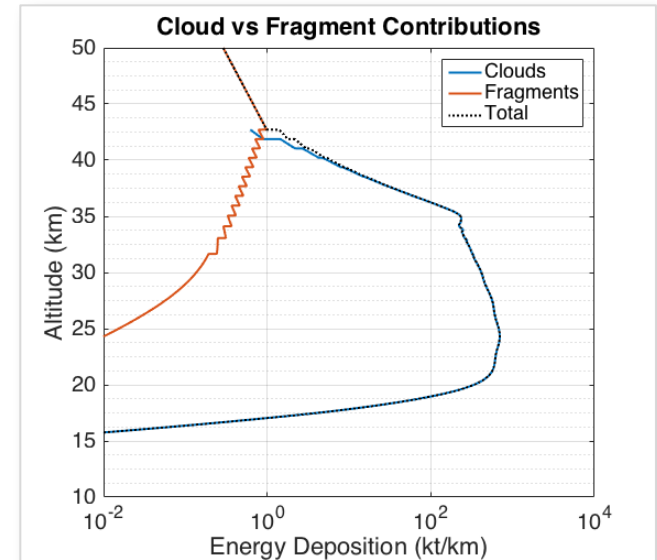
$$S_{child} = S_{parent}(m_{parent}/m_{child})^\alpha$$

## Clouds broaden and slow under common bow shock

$$v_{disp.} = v_{cloud}(C_{disp}A\rho_{air}/\rho_{debris})^{1/2}$$

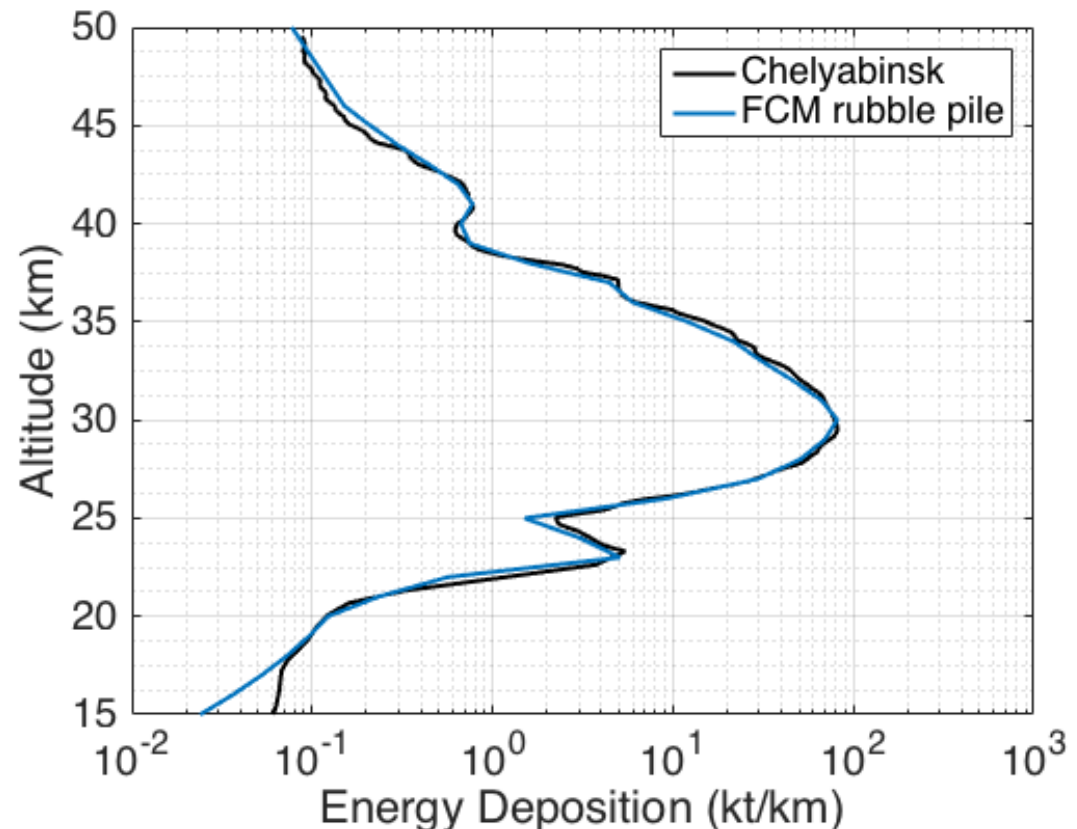
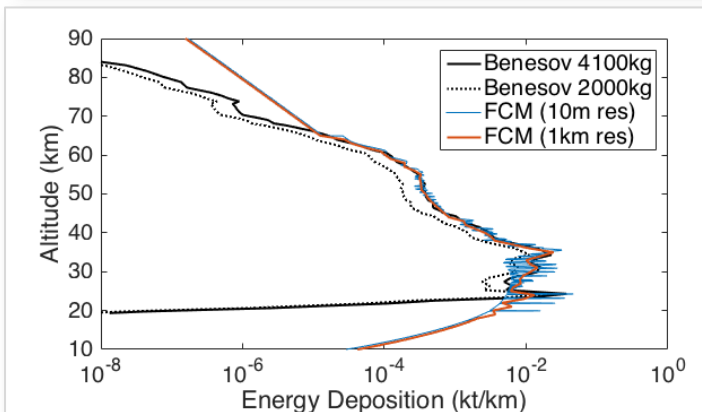
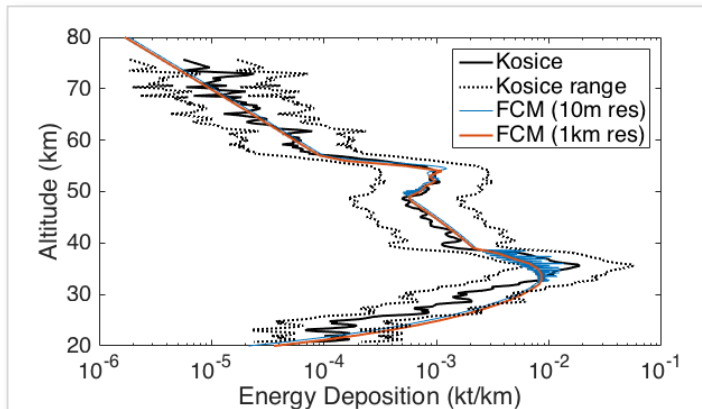
# Energy Deposition ('Edep')

- Energy deposition computed as change in total kinetic energy of all fragment and cloud components as a function of altitude (kt/km)
- FCM energy deposition mechanisms:
  - Debris clouds deposit the bulk of the energy as they rapidly spread
  - Fragments serve to distribute the release of varied cloud masses
  - Large clouds released higher up produce broad, gradual flares
  - Small clouds released lower down produce sharper spikes



# Observed Meteor Modeling

- FCM approach combined with variable initial structures can match a range of energy deposition profiles and features from observed meteor light curves.



# Chelyabinsk Modeling Approach

- Initial entry and mass estimates (Popova et al. 2013):
  - 19.8 m diameter
  - 19.16 km/s at 18.3°
  - 3.3 g/cm<sup>3</sup> meteorite-based density
- Vary FCM inputs to match energy deposition profile from observed light curve (Brown et al., 2013).
- Parameters are set as initial inputs and are not tuned along the entry.
- FCM parameters varied:
  - Initial rubble fragments/debris
  - Initial aerodynamic strengths
  - Number and mass distribution of fragments per break
  - Cloud mass fraction per break
  - Strength scaling exponent ( $\alpha$ )
  - Ablation coefficient ( $\sigma$ )
  - Cloud dispersion coefficient ( $C_{disp}$ )

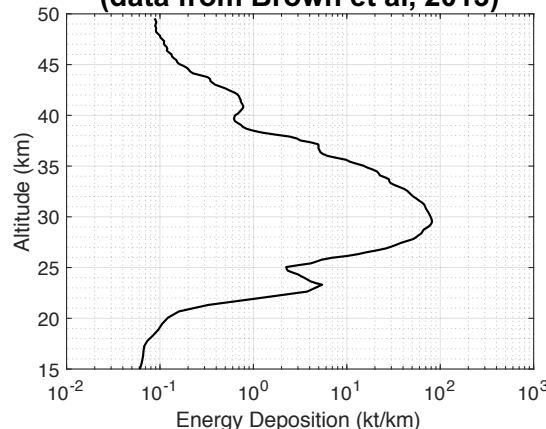
Observed Light Curve



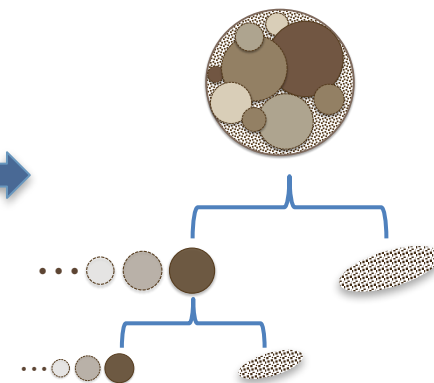
Credit: Aleksandr Ivanov, creative commons license  
[https://en.wikipedia.org/wiki/Chelyabinsk\\_meteor](https://en.wikipedia.org/wiki/Chelyabinsk_meteor)



Energy Deposition from Light Curve  
 (data from Brown et al, 2013)

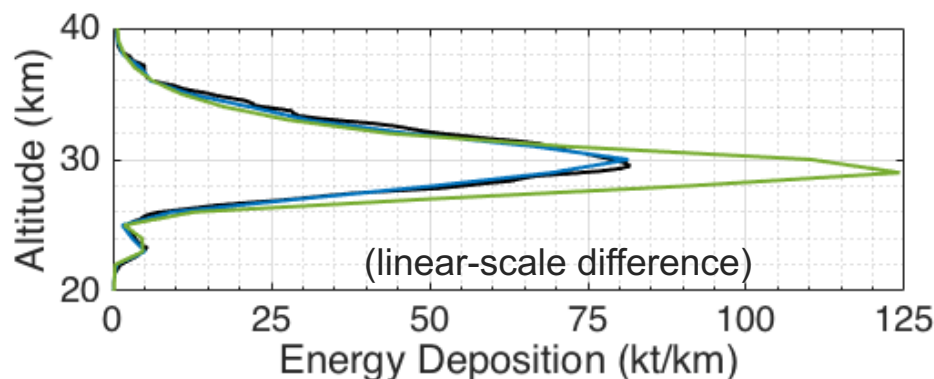
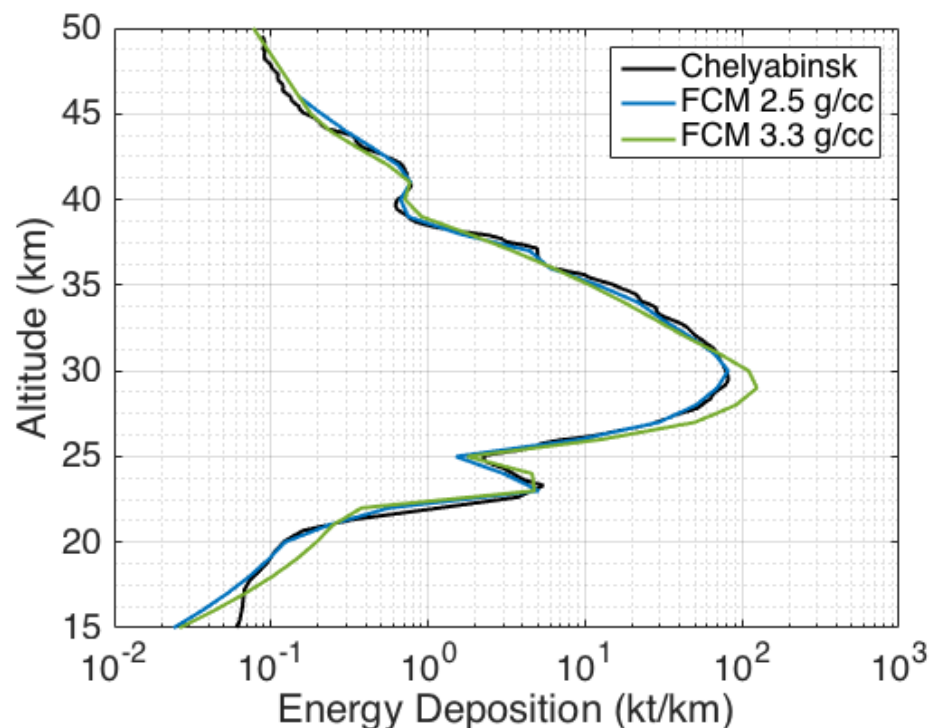


FCM Breakup Modeling

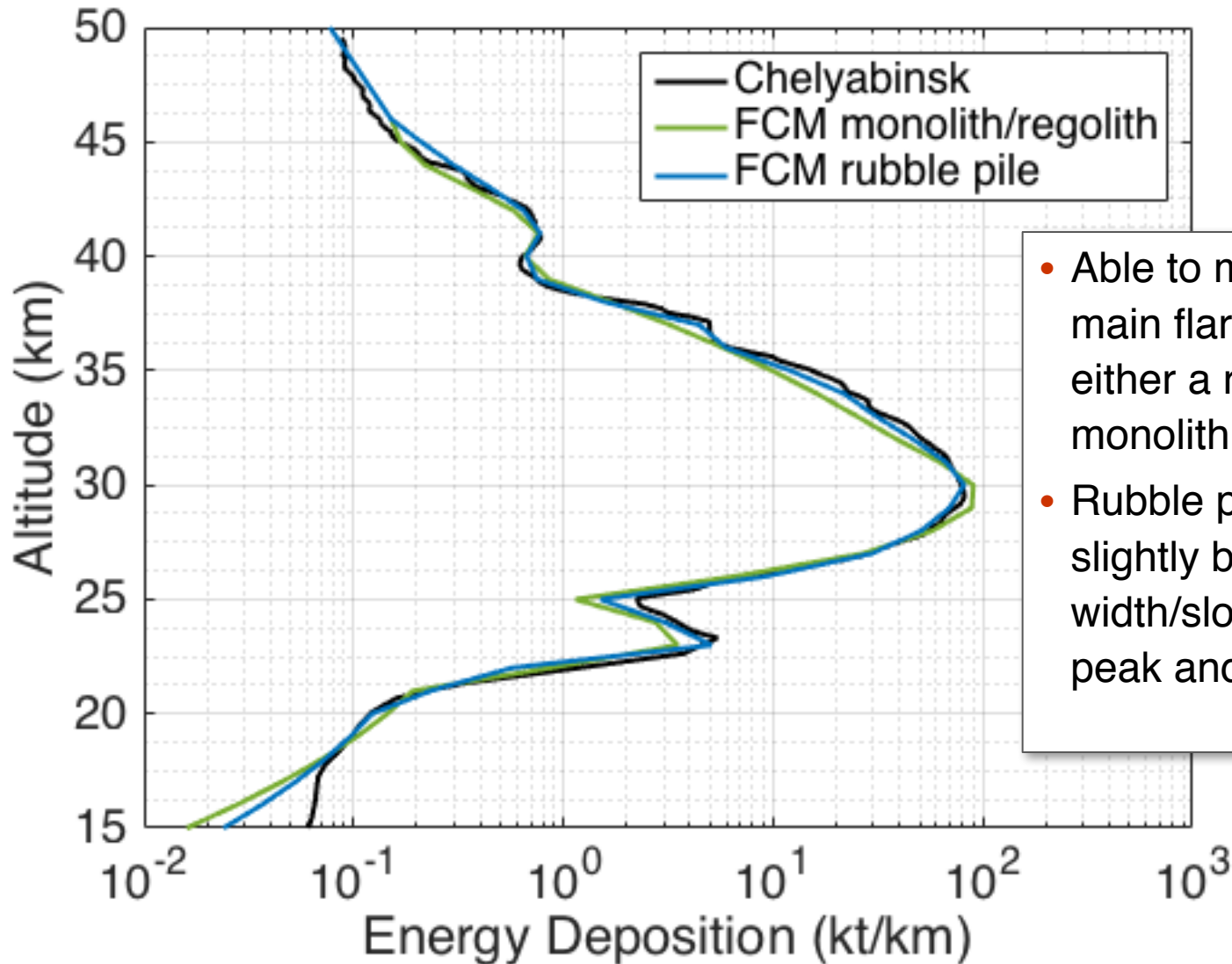


# Pre-Entry Density/Mass

- Cases using meteorite-based density (3.3 g/cc) consistently exceeded peak energy deposition by ~50%
- Lower initial mass and bulk density better matched peak energy deposition
  - 9-10M kg (reduced from 13M kg)
  - Bulk density ~2.2–2.6 g/cc
  - Maintained 3.3 g/cc material density
  - Gives macroporosity ~21–33% compared to meteoritic density
  - Consistent with macroporosity ranges between fractured bodies (15–25%) or rubble piles (30–70%) (Britt et al., 2003, Asteroids III).

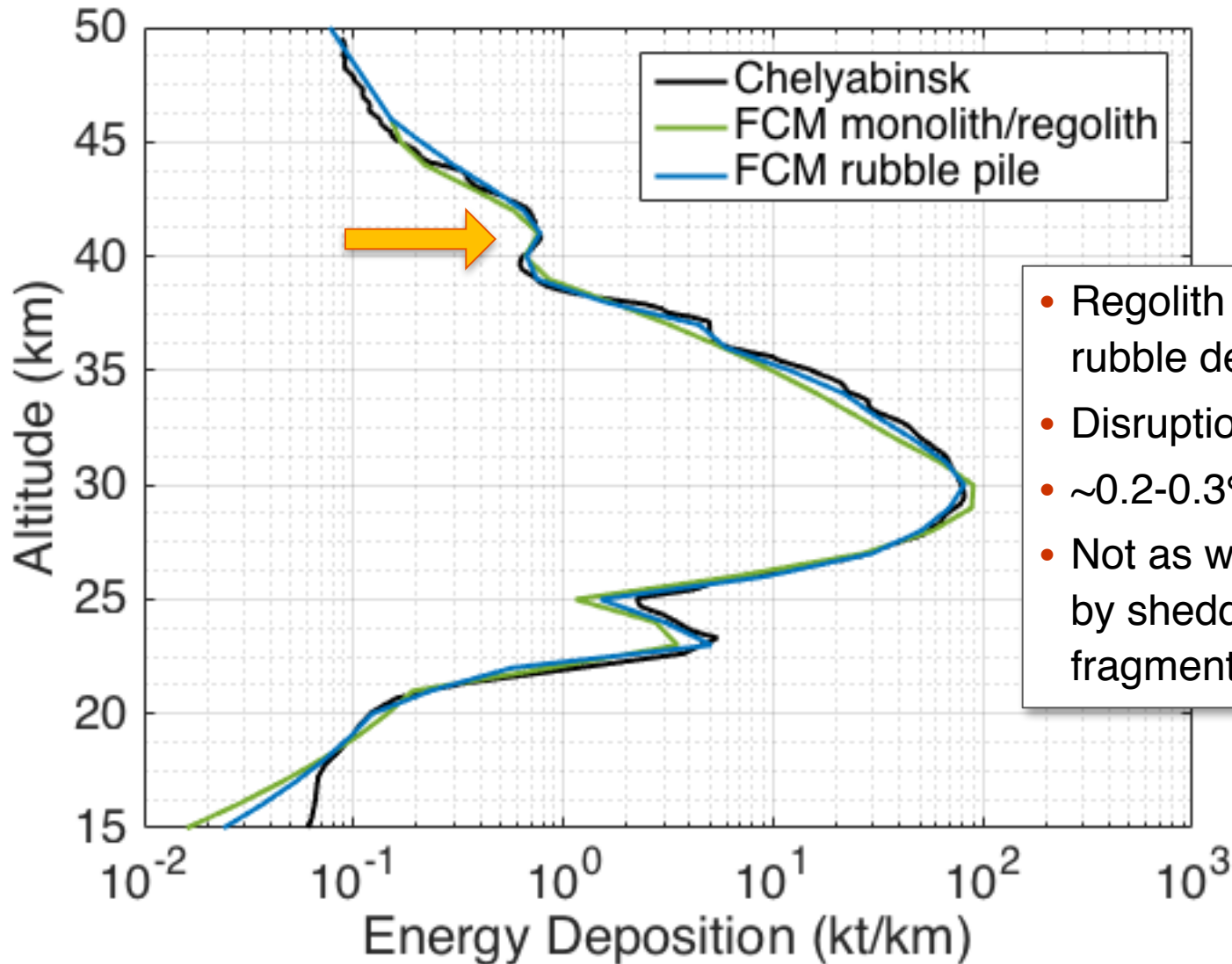


# Pre-Entry Structure



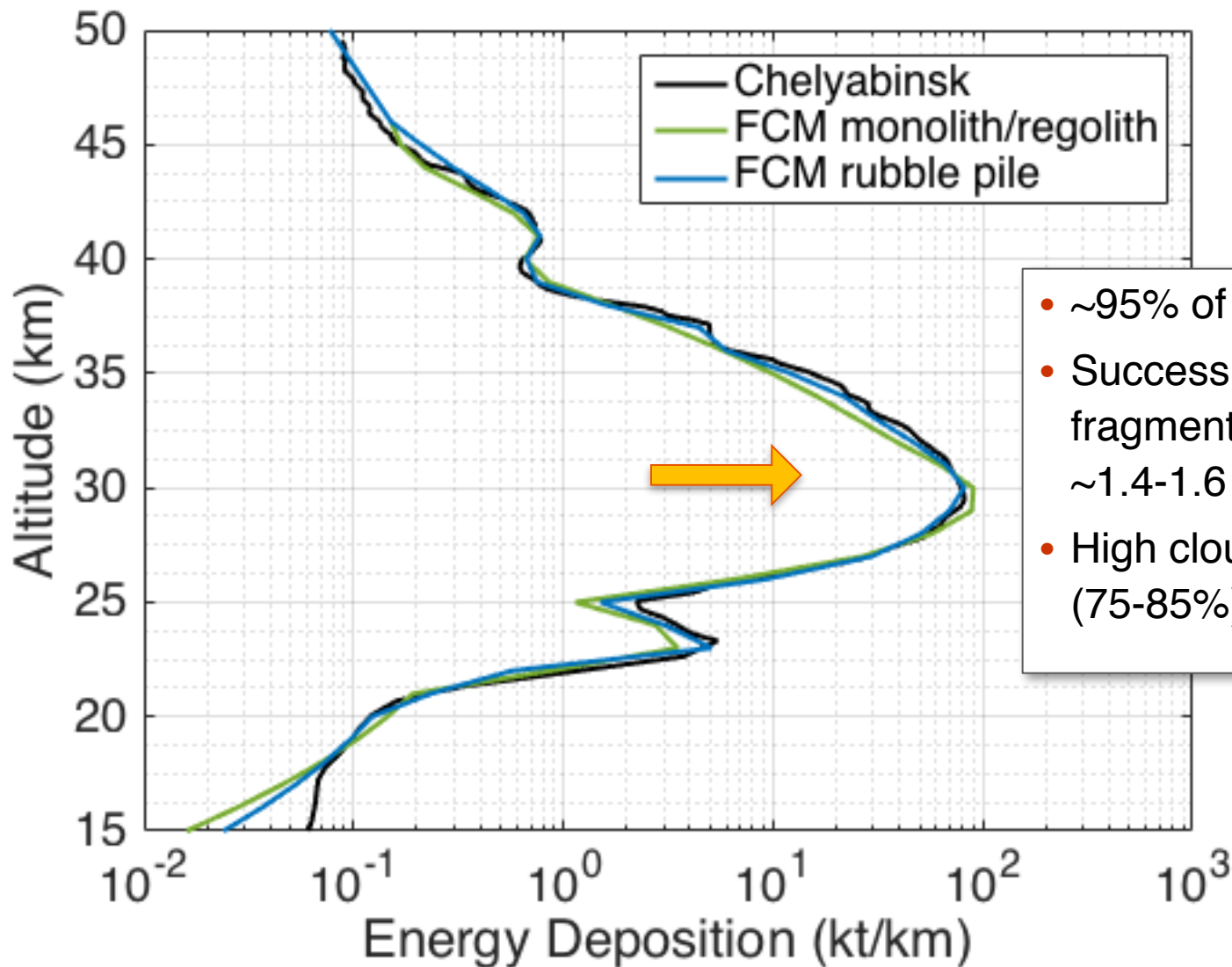
- Able to match all three main flare features using either a rubble pile, or a monolith with regolith.
- Rubble pile provides slightly better fits to the width/slope of the main peak and the lower peak

# Flare Characteristics: Upper Flare



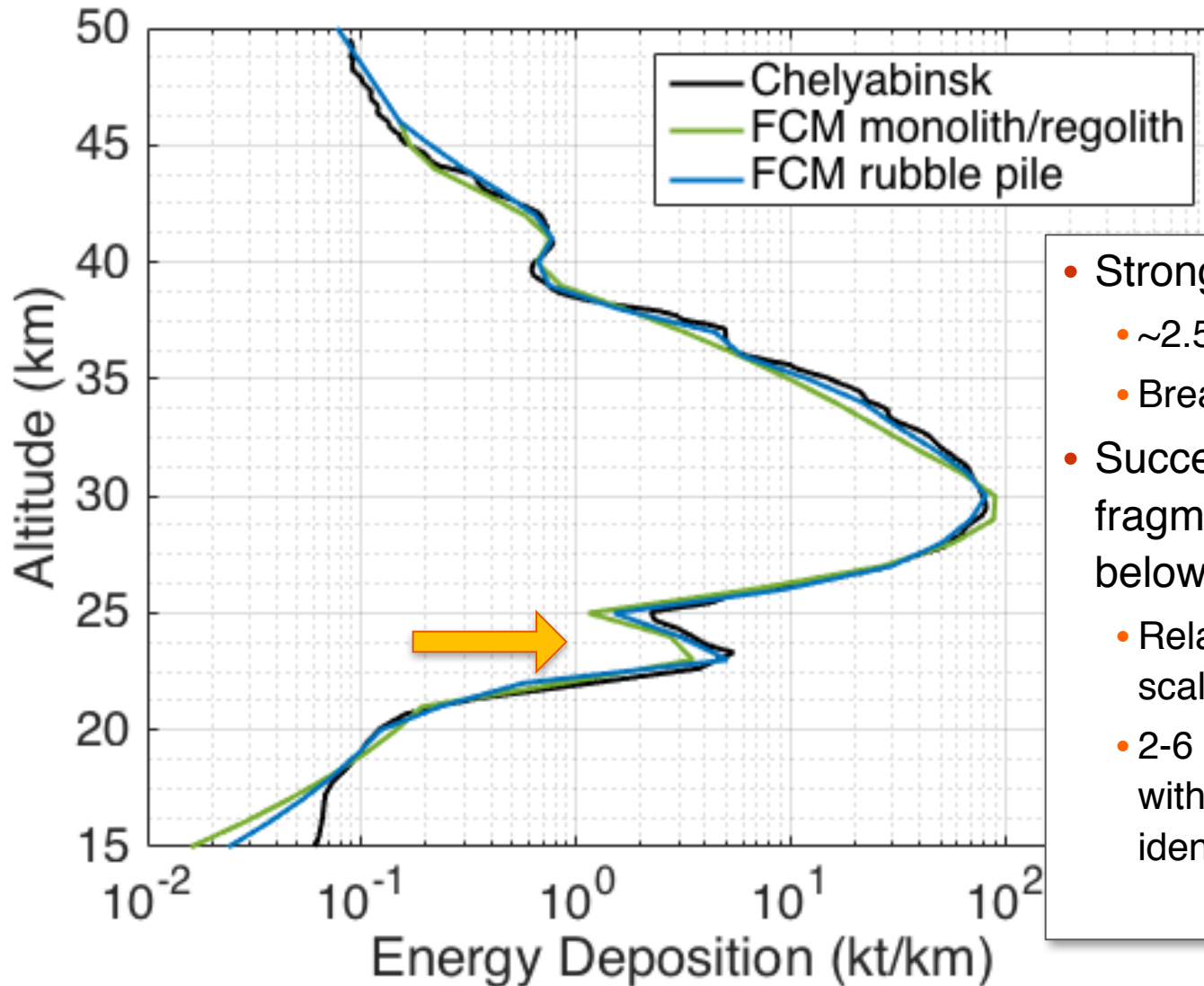
- Regolith blow-off or rubble debris
- Disruption  $\sim 0.5\text{-}0.6$  MPa
- $\sim 0.2\text{-}0.3\%$  of initial mass
- Not as well reproduced by shedding of small fragments

# Flare Characteristics: Main Flare



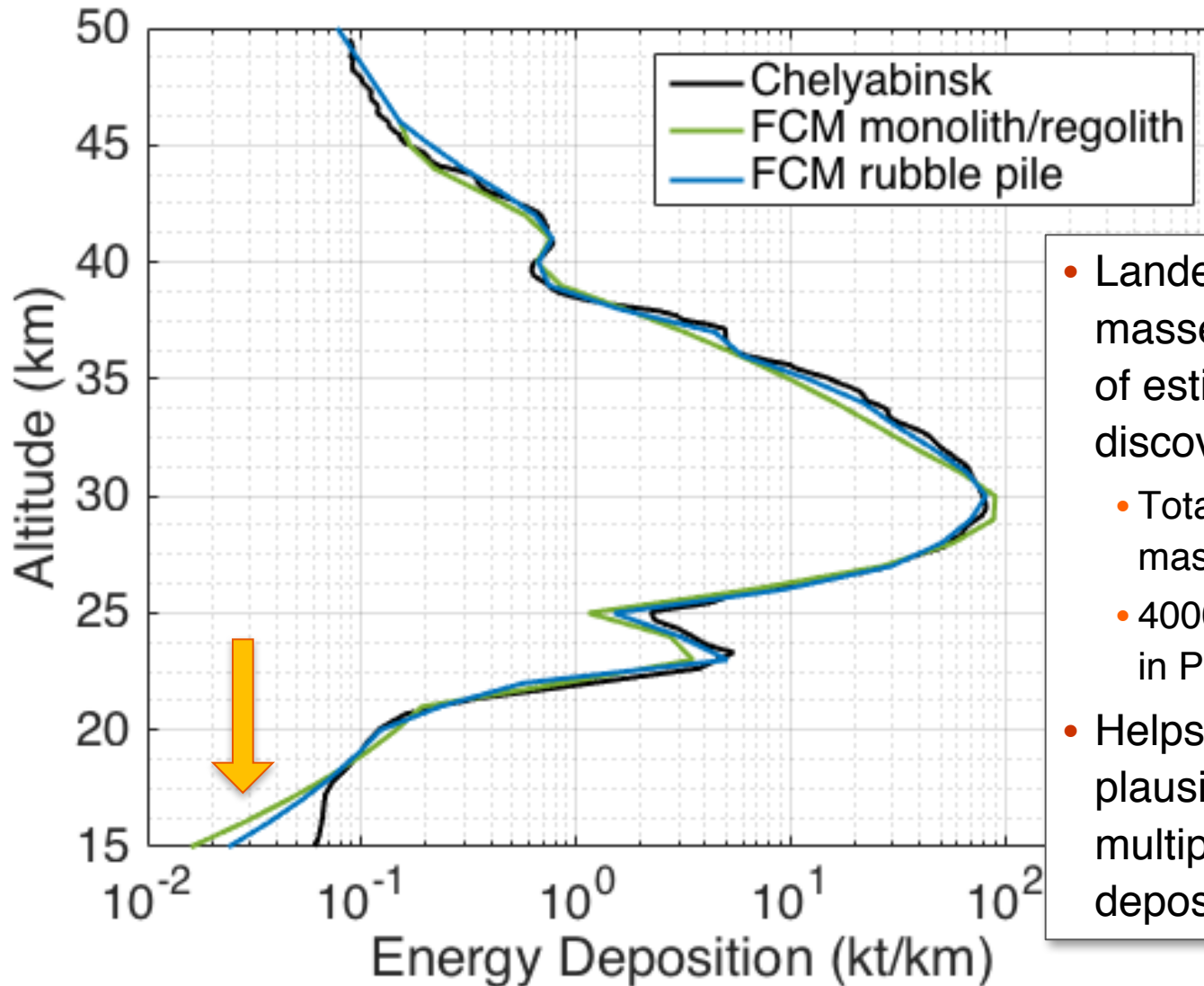
- ~95% of initial mass
- Successive fragmentation beginning ~1.4-1.6 MPa
- High cloud mass fraction (75-85%)

# Flare Characteristics: Lower Flare



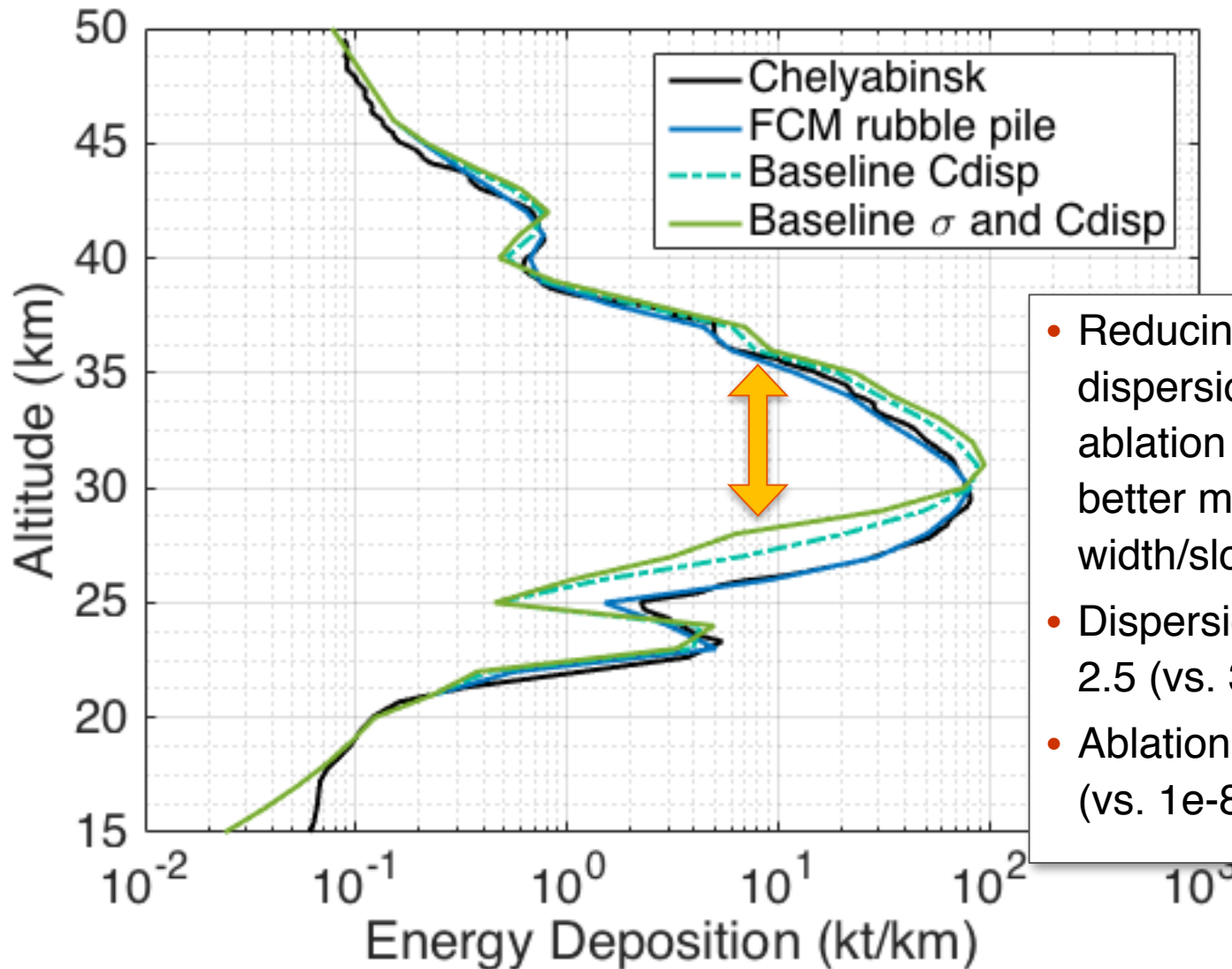
- Stronger initial rubble:
  - ~2.5% of initial mass
  - Breakup at ~15.5 MPa
- Successive fragmentation persisting below main flare
  - Relatively high strength scaling  $\alpha$  (0.3-0.5)
  - 2-6 fragments per break with close (but not identical) mass splits

# Landed Fragment Mass



- Landed fragment masses within ballpark of estimates from discovered falls
  - Total fallen fragment mass 5000–6500 kg
  - 4000–6000 kg estimated in Popova et al. 2013
- Helps constrain the most plausible cases from multiple energy deposition matches

# Cloud Modeling Refinement



- Reducing cloud dispersion and/or ablation coefficients better matches width/slope of main peak
- Dispersion  $C_{disp} = 1.5-2.5$  (vs. 3.5 baseline)
- Ablation  $\sigma = 4-8e-9$  kg/J (vs.  $1e-8$  baseline)

# Summary & Future Work

- Developed FCM capability for modeling breakup and energy deposition of different asteroid structures
  - Produces realistic variety of energy deposition features, enabling very good matches to observed meteors.
  - Demonstrated how we can use those matches to make inferences about asteroid characteristics.
  - Found potential parameter refinements for modeling debris clouds.
- Risk assessment applications
  - Analytic approach efficient enough to run the large numbers of cases needed for probabilistic risk assessments, yet variable enough to represent a wide range of potential asteroid structures.
  - Provides a way move beyond the typical point-source estimates and incorporate the different energy deposition rates into ground damage estimates.
- Ongoing and future development:
  - Initialize rubble pile distributions using inverse power law distributions of sizes.
  - Refine parameters for cloud spread rates using hydrocode simulations
  - Explore effects of varied energy deposition profiles on ground damage compared to point-sources estimates (CFD simulations)
  - Automate a curve-matching optimizer to enable more comprehensive inference and thorough exploration of the parameter space
- Paper available online: **L.F. Wheeler et al., Icarus (2017)**, A fragment-cloud model for asteroid breakup and energy deposition. <https://doi.org/10.1016/j.icarus.2017.02.011>